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G. E. Valley, Jr.

George E. Valley, Jr. (SM'55) was born in New York, N.Y., September 5, 1913. He graduated from the Massachusetts Institute of Technology, Cambridge, Mass., in 1935, and received the Ph.D. degree in physics from the University of Rochester, N.Y., in 1939. Following two years of post graduate research at Harvard University, Cambridge, he returned to M.I.T. in 1941.

During the war he was project engineer for the H_2X radar bombing system, the first American development of this type, which was used extensively by the U.S. Eighth Air Force over Europe and later by other heavy bomber units. In 1945 he served on the editorial board for the M.I.T. Radiation Laboratory Technical Series. Returning to M.I.T. in 1946, he has been successively assistant, associate, and full professor of physics, and has conducted research in the fields of nuclear physics and cosmic radiation.

A member of the Air Force's Scientific Advisory Board since its inception, Dr. Valley was asked in 1949, by the Chief of Staff, to undertake a special study of U.S. Air Defense. The *ad hoc* Air Defense Systems Engineering Committee, which he led as a result of this request, conceived the basic ideas of the SAGE System and was directly instrumental in the founding of the M.I.T. Lincoln Laboratory. Dr. Valley served as division head, assistant, and associate director of the Lincoln Laboratory and was in charge of the SAGE System. In 1957 he went on leave from M.I.T. to become Chief Scientist of the U.S. Air Force.

He is a Fellow of the American Physical Society, and holds a Certificate of Appreciation from the U.S. Army, the President's Certificate of Merit, the Air Force Association Science Award, and the Air Force Exceptional Civilian Service Award (twice).

Guest Editorial

SOME of the earliest proposals for the development of engines of war, complicated enough to be called "weapons systems," were made during the Renaissance by the great Italian painter, Leonardo da Vinci. Many people have looked at his drawings of tanks, airplanes, and other devices with amazement, not only that these should have been conceived so many years ago, but also that they should have been conceived by an artist.

The writer has shared this feeling, but the more he has tried to understand what it is that systems engineers do, the less surprised he has become that Leonardo was an inventor, and the more he wondered why other systems engineers besides Robert Fulton and Samuel F. B. Morse have not also been artists by profession.

For when a painter takes up his palette and brushes, he can create either a masterpiece or a daub; and so it is with the systems engineer. Each of these men must be able to synthesize a satisfactory pattern to be constructed largely from the components at hand—in the one case, canvas and paints, in the other, copper and cores and bits of crystal. Although the systems engineer is the captain of a team, whereas the artist works alone, he must nevertheless make the final decisions; there are relatively few successful systems which were synthesized entirely according to the majority vote in a committee. Nor will anyone who has managed the development of a system readily admit that the systems engineer requires less of that blind persistence in the face of seemingly endless frustration than does the artist starving in the proverbial garret.

It may appear, then, that the quality of the painting depends more upon its creator's vision and courage than upon his ability to run a paint factory. But history contradicts: for although we cannot say with certainty that any great number of masterpieces has been denied us because the paint was of poor quality, we do know that almost without exception the great masters engaged themselves in the development of paint and other components of their art.

And so it is with systems; the system which works and gives years of reliable service is scarcely ever the one which was engineered by a man so ignorant of components that he could not see to it that reliable, tested ones were used nor so optimistic that he allowed all of them to be specially invented for the immediate purpose.

The above is by way of asserting that systems engineering is an art; this statement cannot be proven. What can easily be demonstrated, however, is that the subject of systems engineering is notably lacking in one of the principal characteristics of a science. There is no general agreement on the definition of the words "system" and "systems engineering," for one man's "system" is another man's "component." It depends upon who you are and what

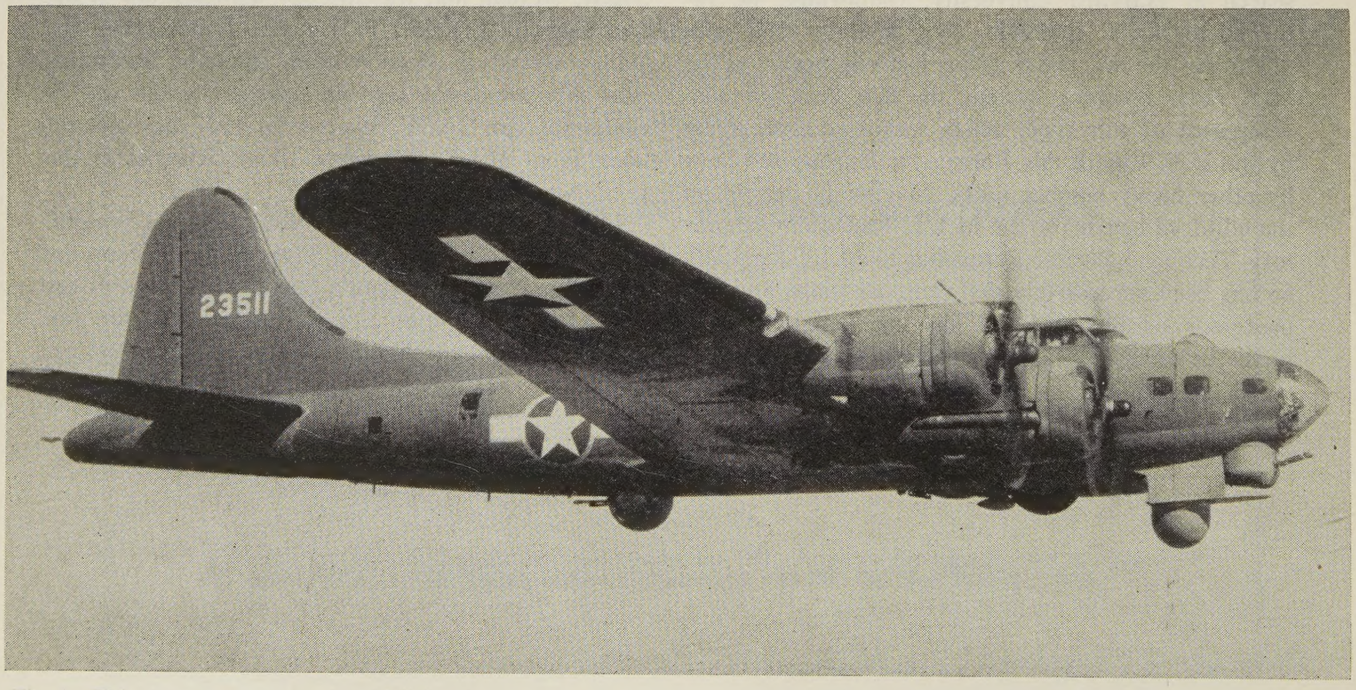

Fig. 1—This photograph of the first U.S. bomber to carry an American-made radar bomb-sight may be of historical interest to readers.

you're doing. There are, for instance, the solar system, the banking system, and the nervous system. The writer's conclusion from reading a good many of the attempted definitions is that all of them can be logically extended to cover devices which are clearly not "systems" and clearly have not been "systems engineered." From this, one can only conclude that practically anything which can conceivably be taken apart and put back together again can be regarded as a system, and that some place there exists someone who regards himself as competent to engineer the procedure.

This reasoning shaped the make-up of the present issue of these TRANSACTIONS. Systems engineering was regarded as a skill to be learned from practice and from coaching by more experienced persons, like learning to play a game—or to paint a picture.

One could not in consequence separate the issue into logical subdivisions of the over-all subject like an arithmetic book. Instead, here is presented the experience of several systems engineers. What these men have acquired is not so much knowledge which can be dissected and set down piecemeal, but an entirely different mental attribute: the one we call wisdom. All the following papers, therefore, bear essentially the same title. They are written by men of the highest stature and achievement in the field, men who have generously given their time to prepare these articles in the hope of passing on to the rest of us a little of what they have learned.

The editor felt no obligation to delete repetitions of the same idea as expressed by the different authors, for if several men independently express the same opinion, it is probably truer than if only one does so; and certainly it is the more easily understood. For the opposite reason, there was no attempt to make the papers consistent with one another, or with this editorial.

George E. Valley, Jr.

Systems Engineering and Weapon System Management*

L. I. DAVIS†

Summary—**Weapon System Management is a term in common use. The author describes some of the problems encountered in developing complete air weapons for combat use. The design problems caused by introduction of jet engines, missiles, and complex electronic systems, in the post-World War II period engendered a developmental pattern which emphasized the need for integration of all components. System engineering, in the control engineering connotation, and operations analyses are necessary parts of the management of modern military weapons.**

A NEW GADGET was added to the Norden bombsight in 1943. It was a "good gadget"—it performed well in engineering tests and was extensively tested by stateside crews before release for combat use. Group commanders in England claimed improved scores when training new crews. But, over Germany, it was another story! Lead bombardiers, old hands, tried it a few times, then adopted the practice of turning it off on the final bombing run.

This device was the automatic gyro leveling attachment, consisting of mercury switches which closed circuits when the gyro gimbals were not level, sending current through torquing solenoids which caused the gyro to precess to correct the condition sensed by the mercury switches. It was a substitute for the visual bubble levels used by the bombardier to erect the bombsight gyro to the apparent vertical. The operation of this gadget is a good example of the need for system engineering. Why lead crews turned it off during the bombing runs over Germany will be explained later in this article.

The lack of success of the automatic gyro leveling device illustrates the many lessons learned during World War II. The period immediately after the end of the war was a time of adjustment and appraisal. Military men shifted from the problems of demobilization to the job of analyzing the lessons of the conflict and the significance of air power on strategy and force composition.

Aeronautical engineers learned a lot from the headaches of trying to make a combat weapon out of an assembly of airframe, engine, and equipment. One difficulty arose from the fact that airplanes are designed with the expectation that a certain thrust will be available at a specified altitude. If the engine propeller combination fails to deliver the expected thrust, the airplane operates off the design point, with serious loss in aerodynamic efficiency.

Another headache might be called "May and December" marriages; for example, airframe and engine combinations each representing the most advanced design practice in its field, and compatible with each other, were loaded down with equipment and armament that was of World War I design.

Turning from engineering to administrative matters, scheduling problems were always plaguing the assembly plants. Long lead time items such as fire control systems, bombing systems, and engines were never delivered on schedule. This was inevitable because the airframe could be built and wrapped around the assembly almost as quickly as the salesman promised. The fact that the airplane builder had no contractual control over the G.F.E. (government furnished equipment) added to the confusion.

Ancillary equipment—ground support items such as tractors for towing, fuel servicing trucks, test instruments, and crew training devices were overlooked in provisioning the combat commands—or were not funded because their priority was not associated with the combat weapon itself.

Turning from some of the lessons learned in World War II to the problems posed by an advancing technology in the immediate postwar years, aeronautical engineers found 1) new propulsive devices—jet engines, ramjets, and rockets; 2) new and demanding military requirements; 3) complex communications, radar, navigation, fire control, and bombing equipment; and 4) missiles and all the design problems of complete automatic control.

The new power plants were voracious in their consumption of fuel, and the thrust-speed-altitude relationships made possible a new regime of operation. These considerations led to many design studies, which surprised military planners, especially when they produced fighter designs that were heavier than the "heavy" bombers of World War II. As a consequence, designers questioned the practice of issuing "Military Characteristics" that specified range, altitude, minimum acceptable top speed, takeoff and landing roll, equipment to be carried, and engine to be used. They rightly claimed that such a rigorous description constrained the design to a single end—and if the product was not what the military expected, the military should blame itself because industry could not change the laws of thermodynamics nor the laws of motion as set forth by Newton.

The military "requirement" to carry 10,000 pounds 10,000 miles brought Breguet's equation[1] out of the dust of the textbooks. As a result, design studies emphasized weight reduction, and every pound of equipment weight was questioned. Aeronautical design has always placed a

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[1] Range in miles $= \text{constant} \times \dfrac{\text{propulsive efficiency}}{\text{specific fuel consumption}} \times \dfrac{\text{lift}}{\text{drag}} \times \log \dfrac{\text{initial gross wt.}}{\text{weight less fuel}}.$

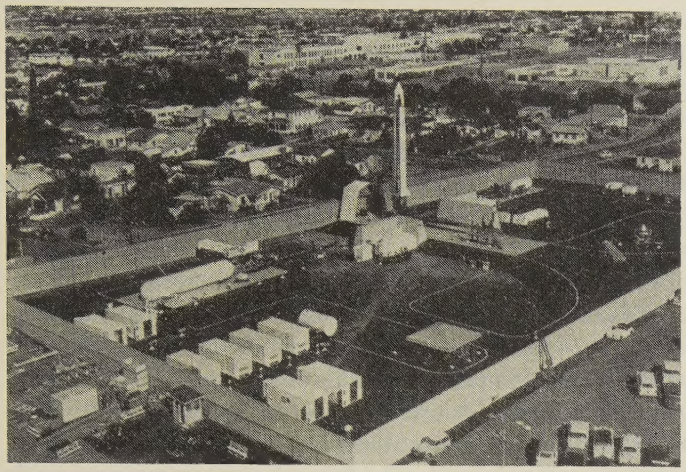

Fig. 1—Thor missile operational launching complex.

premium on efficiency because each pound must carry much more than its own weight. An airplane built to the safety factors used in bridge design will not get off the ground. In addition, the loss in the propulsion efficiency term, because of the new jet engine, brought more pressure to reduce weight. Equipment designers were warned daily that each pound of extra weight carried to the target meant sixteen or twenty pounds more in takeoff gross weight. The problem is the same in missiles. An additional pound accelerated to warhead velocity means fifty pounds additional in the lift-off weight of a ballistic missile.

About this time (1948) the term Weapon System Management began to be used in the Engineering Division of the Air Materiel Command of the USAF as a result of the lessons learned in World War II and the problems posed by the new jet engine, missile, A-bomb technology.

This term was the outgrowth of discussions held among the engineering laboratories, the aircraft and missile project offices, and engineering management in the persons of Generals Chidlaw, Craigie, Crawford, and Putt. The laboratories, conscious of the critical nature of system designs in which coupling and feedback caused dynamical problems, pressed for the establishment of an agency responsible for "systems" engineering. The aircraft and missile project offices recognized this need and, in addition, the administrative problems of scheduling long lead time items, ancillary equipment, and training devices. Engineering management recognized these problems and also the problems of system optimization in a combat as well as in an aerodynamic sense.

The word "Weapon" emphasizes efficiency in combat as the goal. The word "System" emphasizes the desire to integrate all elements—to have a complete package to deliver to the using combat command. The term "Management" implies the sound administrative practices required to plan all elements and to schedule components, testing, ancillary equipment, and training.

Consideration of the tremendous job of integrating into one complete design the characteristics of tens of thousands of components, the procurement of parts on subcontracts, the scheduling of long lead time articles, the parallel development of ground handling and test equipment, plus the very specialized talent required for operational and systems engineering studies, lead to only one solution: develop weapon systems by a prime contract with one agency, with a "weapon system manager."

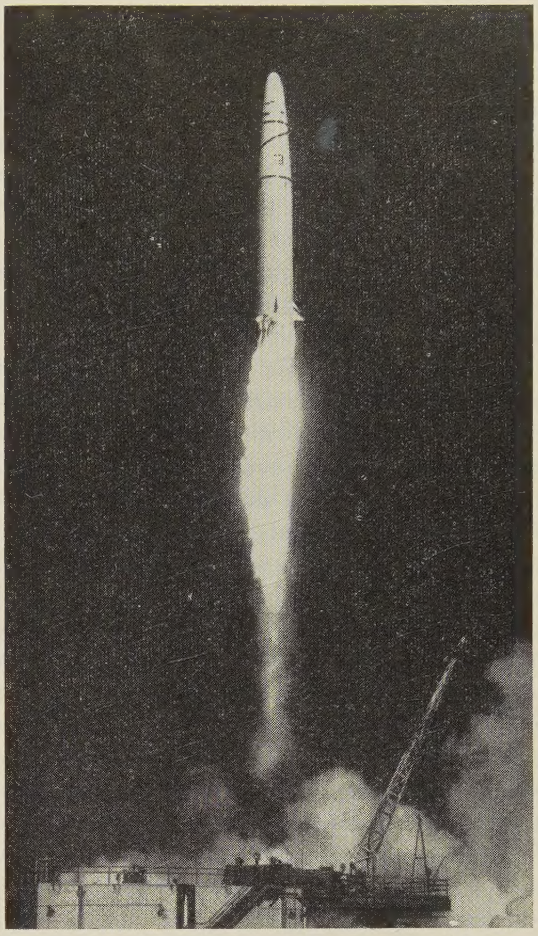

Fig. 2—Thor missile shortly after launching.

Industry, at least those firms which had the breadth and depth to compete, welcomed this procedure. They had a sincere desire to do a good job by furnishing to the military a really integrated weapon. In addition, the aircraft industry noted the growth of expensive "equipment." The airframe of the B-17 accounted for 78 per cent of the cost of the combat weapon; however, the airframe of the B-47 cost less than 50 per cent of the weapon delivered by AMC to the Strategic Air Command. So the profit motive entered the picture.

Industry gladly accepted weapon system management. It joined its voice with that of the military (which was patting itself on the back for putting the monkey on someone else's back). The chorus of mutual congratulations swelled so high that the idea acquired the dubious label of "Weapon System *Concept.*"

So many articles have been written and speeches delivered about the "Weapon System Concept" that the need and the origin have almost been forgotten. The need arose from vital systems engineering problems, and the origin of the term came from a desire to manage the planning

and scheduling of a combat weapon as a complete system.

Today, ten years after the origin of the term, we can assess the value of the practice with knowledge based on experience, not theory. In those cases where weapon systems management has been successful, we see a proper balance of emphasis on all aspects of the total problem.

Before "cutting tin," four types of studies are required. "Operations analysis" studies analyze the military problem and attempt to express in quantitative terms the gains or losses in over-all mission preformance effected by emphasis on this or that element of performance.

An example might be cited from our experience in the Korean War. We can look back on the battles between the F-86s and MIG 15s and, with the exquisite accuracy of hindsight, point out that the probability of success in aerial combat is the product of four serial probabilities. The probability of success of a combatant, after the enemy aircraft has been sighted, is the product of the probability of being able to maneuver into position, the probability of closing to effective range, the probability of hitting the target and the probability that those hits are lethal. The final product, the probability of success, is very sensitive to the weakest link in the chain $P_K = P_M \times P_R \times P_H \times P_L$. The MIG 15 had better altitude, acceleration and turning radius than the F-86 plus a cannon with explosive shells. The weak link was the probability of hit term. Under the very dynamic conditions of high-speed jet combat, a good operations analysis study would show emphasis should be placed upon the fire control equipment which assists the pilot in aiming his guns. The F-86 was equipped with automatic radar ranging and a gyro gunsight designed by C. S. Draper of M.I.T. Automatic range finding relieved the pilot of estimating or visually measuring range by stadiametric means, and the gyro computing gunsight computed the correct lead in inertial space coordinates with minimum dynamic error. The final box score on F-86 vs MIG engagements shows a ratio of about 15 to 1 in favor of the fighter with the more sophisticated fire control equipment.

The second type of preliminary study is the classical performance study on range, altitude, speed and payload with the propulsion units available.

The third type of study concerns itself with system dynamics—commmunications, computation, data processing and control. Accuracy studies lie in this class because of their dependence on the analysis of dynamic error introduced in data handling, computation and control. If system dynamics are ignored, the kind of trouble is experienced that was encountered when the automatic gyro leveling device was introduced into combat.

The fourth type of study before engineering models are constructed deals with research on the state of development of component parts. The decision to start a full fledged weapon system project should be made on the basis that the probability of successful solution of unknown features of the design is reasonably high. If management chooses "off the shelf" "proven" components, or waits till all components are thoroughly tested, the final product will be obsolete when it reaches the field. If, on the other hand, management elects to introduce too many new design features, the probability of success is rather low, and the probability of meeting operational dates approaches zero. It has been said that we cannot schedule invention, that some things require a fixed gestation time, and the period is not shortened by putting more people and money on the problem.

After the design of the weapon has been agreed upon, and fabrication has begun, "weapon system" management can look to the details of ground handling equipment, fuel servicing equipment, checkout consoles and other logistic support items. Crew training must be scheduled in advance of equipment, of course, but the actual training must wait until prototypes are available, and until experience with developmental testing reveals the methods and skills required.

Developmental testing is more than "proof testing" of a model. Modern high-performance missiles are much more sophisticated than a mere assembly of tested parts. Each part is designed to carry its load and perform its function with minimum weight and power. If the original design does not fail when first subjected to full-scale load tests, it was probably overdesigned. Developmental testing is a process of probing for weaknesses, redesign, refabrication and retesting, first of prototypes, then of articles made by production tooling.

Good system management plans for thorough testing for fabrication of sufficient articles so that the testing can be done in parallel; it recognizes that performance is affected by production methods, tooling, and quality control as well as engineering design. Therefore, the testing phase is not complete until the product of the production line has been handled by combat troops in an operational environment.

In this connection it is appropriate to emphasize that a proper balance between component and complete system testing is necessary. If system testing is delayed until elaborate component testing is complete, the over-all cycle is unnecessarily extended. Although system testing is more expensive, there are a great many component as well as system weaknesses that will not be found until complete systems are tested on the ground and in flight.

On the other hand, in those cases where systems produced by "weapon system" management have failed, we see attempts to short-cut the foregoing studies and steps. In most cases the attempt to buy time with money produces unreliable systems much later than the operational dates promised. Management, unskilled in system engineering, attempts to break down the design in many components, to be produced in parallel. Many times it is "easy to do it the hard way" producing overly complex solutions to problems that are relatively simple when reviewed from a total system viewpoint. On the other hand, a really sophisticated design cannot be achieved without extensive system engineering studies to determine the required performance of each component, plus the nature of the inter-

action of components upon the performance of the whole.

The interaction of the performance of components when assembled into a system and operated in the geometry of the combat situation brings us back to the example used in the introduction of this article.

Why did the automatic gyro leveling attachment fail to perform satisfactorily over Germany?

The system, consisting of the gyro (which stabilized the bombsight optics), the bombardier, the auto pilot, the airplane and the gyro leveling attachment, had a definite feedback path. The bombardier, in keeping the crosshairs of the optics on the target, sent signals through the auto pilot to correct the heading of the airplane. The acceleration of the plane as it changed its heading was sensed by the mercury switches of the leveling device and interpreted as a change in the apparent vertical. This in turn caused the gyros to precess—moving the optics. The sense of the correction appeared to be degenerative or stable if one ignored phase shifts, and certainly there was nothing that looked like tight coupling or high gain in the system.

When the phenomenon of hunting or oscillating on high altitude bombing runs was reported to the Armament Laboratory in 1944, a stability analysis was made. The methods used were those set forth in den Hartog's text, "Mechanical Vibrations." When the geometry of the problem, the phase shift in gyro precession, erection rates and reasonable assumptions about response times were cranked into Routh's stability criteria, it was apparent that stability was a function of altitude. To the electrical engineer the 90° phase shift in the gyro part of the loop would be obvious and a danger signal. The "gain" around the loop does not become apparent until a study of the geometry of the action shows the airplane pivoting about a radius that is the projection on the vertical of the line of sight to the target. The greater the altitude, the greater the radius and acceleraion. Thus, the "gain" increases with altitude—and at the extreme altitudes of the combat bombing runs over Germany a low-frequency hunt or oscillation was experienced. Experienced bombardiers broke the feedback loop by turning off the automatic device. They leveled the bombsight by visual reference to the bubbles when the plane was in straight and level flight.

"Weapon System" management has been outstandingly successful in the ballistic missile program. This has not been achieved by a single prime contract, nor by "concepts" or programs or printed schedules. The success is due to the fact that systems engineering is done under a separate contract. General Schriever has in effect raised it to top management status, and objective studies and research can be conducted unbiased by sales and production pressures. Schedules on subcontracted items and comprehensive testing can be established in that same atmosphere.

The bright and shining label "Weapon System Concept" will not solve our system engineering problems, nor will it change the fact that it takes twice as long to develop a missile propulsion plant as it does to wrap the tin around it. The work that needs to be done still has to be done by people who deal in facts, not labels and who have the training and experience and patience to find simple but sophisticated solutions to complex problems.

Systems Engineering for Usefulness and Reliability*

W. C. TINUS† AND H. G. OCH†

Summary—**With the increasing complexity and cost of weapon systems, it is becoming ever more important to provide a product that will be useful to the customer, that will provide reliable service, and that will have growth capabilities so that its useful life can be prolonged to meet the ever increasing enemy threat. The management of the research and development program for such large projects must provide detailed and careful planning and control in order to produce an integrated system on a minimum schedule.**

System approach, now the byword of the electronic industry, means many things to many people. To the authors of this paper, it is the orderly arrangement of many details that are necessary to the sound planning of a large development effort.

IDEALLY, a development program results in equipment which comes into operational use at the time it is needed and performs its intended functions well, serves its user with a practical maximum of reliability and has a long operational life due to adequate foresight in its concept and inherent growth capability in its design. Additionally, the ideal development is carried out at reasonable cost and the design lends itself to economical manufacture and maintenance.

It is hardly necessary to say that if all development projects could come closer to this ideal, much faster technical progress could be made and much less development effort would be wasted.

It has become more and more apparent in recent years that better over-all planning before large development effort is expended and better checking of plans throughout the development interval, are the only ways to make the results of large development efforts more nearly approach the ideal.

The basic prior planning of developments and the continuing detailed adjustments of these plans during development to insure a well-balanced outcome are the heart and soul of systems engineering. In this paper, the authors have undertaken to discuss in some detail the course of a large development in an effort to illustrate the controlling effect on the outcome of good planning at every step along the way.

A well-planned system development program can be divided into six major phases as follows:

1) Study phase
2) Proposal evaluation
3) System design
4) Equipment design
5) Model construction and test
6) Completion of manufacturing information.

* Manuscript received by the PGMIL, October, 1958.
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Generally, these steps follow in chronological order. However, many of the detailed steps actually overlap and even recur during the development program.

Studying the Problem

Let us begin by examining the first step of our program—the study phase, in which the problem which the customer wants solved is considered. It may be a very concrete problem, and he may have a proposed solution to it which he wants carried out. On the other hand, it may be a very vague problem which has yet to be explicitly stated. The systems study engineers must first attempt to understand the problem thoroughly and to state it explicitly. It must be defined clearly in relation to other surrounding problems, and solutions should be proposed which are compatible with the surrounding problems. The comparison of different possible solutions must be made on the basis of both technical and economic analyses. A proposed solution must be subjected to such broad questions as "Is it timely to undertake any solution to this problem?" and "Who is best qualified to undertake it?"

In the case of defensive military systems, an evaluation must be made of the expected threat in the time period when the equipment will be deployed. Similarly, in the case of offensive weapons, the probable defense posture of the enemy must be examined again as of the time period when the equipment will be operational. Only through careful and objective comparison of the opposing capabilities, at a future realistically estimated time, can reasonable assurance be had that the equipment to be designed will not be obsolete before it finds usefulness. Added insurance can be obtained, of course, by providing, wherever possible in the design, the potential for growth and extension of the design to keep up with the ever-advancing military technology.

In the study phase, it is of extreme importance to evaluate objectively the state of the art available for the project. If a major advance in technology is undertaken, it is necessary that the state of the art be pushed with attendant extra risks. On the other hand, if a completely reliable system is the objective, techniques and devices which are completely proven and are in the state-of-the-art stockpile must generally be used. The first approach, if carried to extremes, would move technology forward with giant strides without ever producing reliable equipment which could be depended upon to function when it is most needed. The second approach, if carried to extremes, would eventually result in being far behind in the technological race. Obviously, a compromise is needed, using as many of the techniques and devices "off the shelf" as possible, while pushing the state of the art forward in a relatively small number of areas where such advances are most urgently

needed. In making the choice of these areas, it is important that concentrated effort be available and applied from the very outset to the major unknowns of the project in order to insure the proper meshing of the development schedule.

The study phase is for gathering ideas. One approach for getting all the hopefully bright ideas on the table is to rule out all evaluation whatever until *all* the ideas, preposterous or not, are on display. This technique is most useful in cases where there is a shortage of ideas for consideration. As all available ideas are boiled down and interrelated, it becomes possible to define the kind of subsystems that are needed and to determine tentative requirements for these subsystems. The backbone of this skeleton of ideas is the plan for time sequential or tactical operation of the system. The mission for the system must be outlined in a step-by-step fashion starting from turn-on of the equipment to "mission accomplished." Without such correlation, the equipment units in a system degenerate into a group of interconnected "black boxes" which are separate entities and do not comprise a system.

When the system skeleton begins to take form, it is time to make a preliminary analysis of system capability. This consists of rough estimates of accuracy, fire power, and such other parameters as are necessary to assure that the conception of the system will be satisfactory. If these estimates show adequate performance capability, and it is reasonably certain that a better approach has not been overlooked, it is timely to proceed with more detailed considerations.

Evaluating the Proposed Solution

The second phase of development may be called a complete evaluation of the recommended system. This evaluation is essential and must be carefully conducted to furnish an enduring foundation for the large development effort to follow. It must be made with the advice and assistance of the equipment design engineers, who will later do the detailed design work, and must go into considerable depth of analysis of the subsystems in order to insure feasibility of the system plan. Over-all system performance requirements must be continually reviewed in the light of these more detailed analyses of the subsystems and components in an attempt to uncover basic technical or economic conflicts. When such conflicts are revealed it is necessary to propose means for designing around them, or to revise requirements to maintain an economic balance.

In this re-examination, a great deal of detailed attention must be given to the human engineering aspects of the system, from the standpoint of fitting the machine to the operators. A careful look must be taken at the proposed division between automaticity and human decision. Time analyses must be made to interleave the operations accomplished by the human operators and the machine. The proposed tactical operation of the system may have to be rearranged in order to minimize total time needed for the mission or to prevent even momentary overloading of a human operator. Displays and controls must be worked out in principle if not in detail to study the probable reaction of human operators to the stimuli of the indicators. Much thought must be given to accomplishing the mission with a minimum of operational controls.

At this point in a development project, it is important to undertake a preliminary assessment of the reliability of the recommended system. The reliability of the system, of course, depends primarily on the reliability of the component parts, all of which can only approach but never achieve 100 per cent reliability. It must be remembered that new ideas for components, or new design techniques, while providing greater technical capabilities, will generally not provide an immediate improvement in reliability. As a matter of fact, new components and design concepts usually introduce new problems and reduce reliability for some time. The eventual reliability of new components is generally better than the reliability of those they replace. However, this results only after experience is accumulated—experience in methods of manufacture, experience in proper design use of the unit, and experience with the unit in an operating system under actual field environmental conditions.

Of critical importance in estimating reliability is a knowledge of environment. Temperature, humidity, shock, vibration, pressure, and other elements of environment during shipment, storage, and use must be estimated so that realistic evaluations of component reliability can be made. Estimates of mean time to failure for the system are essential for comparison with the total mission elapsed time. Inherent potential weak points in the system must be examined and a start made in the planning for maintenance procedures and maintenance test equipment.

The recommended system must also be critically examined in this period to determine if it can be adequately maintained as it will be deployed in the field. Will it be practical to bring test equipment to the system when needed? How much built-in test facilities should be provided? Do the size and weight and operating requirements permit intricate built-in test equipment? Should only "Go-No Go" test facilities be provided? What are the expected technical qualifications of the operators? of the maintenance crew? These and many other questions have to be satisfactorily answered before it is reasonably certain that the recommended system will be an effective one for the customer's use.

Based on this more detailed study of the proposed system, it is important to re-examine the tentative schedules for the project with respect to its prospects for meeting the expected enemy capability at time of deployment. One of the most critical scheduling problems has to do with the technical advances required in the state of the art for completion of the project. A careful assessment must be made of the probability that the necessary technical breakthroughs will be accomplished in time for use in the project. Obviously, this is an area of calculated risk and the project can rise or fall if judgment on this is wrong. This is generally the only area where any consideration should

be given to parallel developments for insurance of success, and the less desirable alternates carried along in development must also be capable of meeting the system requirements or the project is in grave jeopardy.

Outlining the System

Having accomplished this close scrutiny of the recommended system plan and having found all factors favorable, it is now possible to prepare a complete specification of performance requirements. This is the first major step in the establishment of a firm development plan for system design. If the project has been properly handled, this document has already been in process from the very beginning. During the study and evaluation stages, it has become more elaborate and now attains its full maturity in the project as the project "Bible." When reproduced for each group of subsystem designers, it will become the designer's guide and will furnish the basis for detailed compatibility at the interface between subsystems.

During the development processes just described, it is important that all important changes in system objectives be cleared with the customer. Weapon systems usually start with a set of objectives which are highly desirable but probably not completely attainable. It is often necessary that the objectives be modified to a level attainable in the program time scale. This frequently requires the deletion of superfluous emergency modes and operational frills in order to make the design simpler and more practical from a reliability and maintenance standpoint.

The development plan must include a system philosophy to be followed regarding reliability of components. The development organization may already have established reliability standards; however, these are generally broad in nature and it is necessary that the project spell out standards which are tailored to its specific environmental conditions. These will include guides for choosing components of known reliability and the derating factors that are to be used throughout the design. When components must be used whose performance and reliability are unknown, suitable environmental tests must be made and changes in component designs undertaken to insure the consistency of these elements with the rest of the system.

The ever increasing complexity of our military systems has emphasized the importance of minimizing the number and type of manual operations. The development plan for a system must, therefore, include firm requirements on the types and numbers of controls so as to leave the human operators as free as possible to make their major decisions. A system that has too many maintenance adjustments is apt never to be ready when needed. It is important that the maintenance philosophy and planning for test circuitry be available at the beginning of the design period so as to produce a uniformity and optimization of the field maintenance procedures.

It will be obvious that in setting up the philosophies for reliability and maintenance, a number of system performance compromises will have to be made. These may, of course, be reflected by minor changes in the project "Bible" and modifying what was a too optimistic performance to a more practical and reliable level.

On any large job, a system generation breakdown chart is required. This is a chart naming the subsystems and their further subunits so that the assignment of tasks to various development groups can be made. The division into subunits must be made in a way which will produce a separately manufacturable and testable unit for which an individual test specification can be written. A set of requirements for each unit can be made available for all groups working on the project, showing what each unit is expected to do and insuring compatibility at the interfaces between units. As the designers proceed and find that changes need to be made, these specifications must be kept up to date. It is always possible then for the system coordinating group to evaluate the current expected performance of the system.

It is essential that complete schedules for the project be provided and maintained, highlighting all significant mileposts for the basic development, prototype, and production phases of the project. Each identifiable unit on the generation breakdown chart must be scheduled for electrical design, brassboard, laboratory test, mechanical design, model test, subsystem test, and any other significant program check points.

Since the project organization is usually not equipped to design all subsystems, units, or components required in the system, a plan for subcontracting design effort and model production is necessary. It is essential that all schedules and specifications be completely agreed upon with properly qualified subcontracting groups in the same or other companies.

Designing the Equipment

Now an all-out effort is applied to the actual detailed electrical and mechanical design of the system components. Prior to this phase, there has been a concerted attack on the most difficult problems—those requiring major technical advances in the art. Also, prior to this point there may have been several areas where parallel approaches were being studied so as to insure the most effective solution. These by now must be resolved to a single approach, with enough emphasis to insure success in the time period.

Throughout the design phase, there must be a more or less continual re-evaluation of system performance and subsystem specifications to maintain compatibility of design and effect necessary compromises. The amount of this, of course, will depend primarily on the difficulty of the job and the degree of success the individual designers attain on each subunit of the system. A program of periodic meetings of all supervisory personnel on the project is helpful in accomplishing this aim. These meetings may be held on a bi-weekly basis and should be limited to about a two-hour period. Each is led by the project group, and the technical material covered in each meeting is specific to a single area or subsystem. A brief discussion of the objec-

tives and attainments usually uncovers minor incompatibilities and misunderstandings which can then be worked out in detail by the particular engineers concerned, without appreciable wasted effort. These meetings are helpful in maintaining fluidity of thinking in the project and permit even major modifications if and when unexpected technical break-throughs do occur. These meetings also serve to keep the project manager and his system-design group completely informed on progress in each area. These meetings should not, however, take the place of the day-by-day discussions that are necessary between the designers of subsystems which are interrelated or have common interfaces.

During the design phase, as brassboard models are created and tested, it is important that the results of these tests be fed back to the system planning group so that they can perform their function of re-evaluation. As the tests progress, individual designs should be frozen as soon as adequate performance is in sight, so that the final drafting can get under way. No project can afford time to comb out all of the minor bugs from subunit design before starting the drawings for a true prototype model. Good judgment has to be exercised and calculated risks taken in deciding when a design is adequate. The detail frills can be ironed out during the time that the design is on the drafting board, or even while the prototype models are under construction.

Models and Manufacturing Information

Most military jobs are rush jobs and the last two phases in the development program generally occur more or less simultaneously. These involve the construction and testing of the models of the system and the completion of manufacturing information. If everything were ideal, the drawings provided for building of these models could be used directly as a major part of the manufacturing information. However, problems are always uncovered in the fabrication of the models, and operational difficulties are bound to occur during the test of these models. It is necessary to feed back information quickly and accurately to the drafting groups so that manufacturing information can be completed.

A well-developed plan of test is needed proceeding through unit tests and subsystem tests to system tests. In each case, there will be the usual de-bugging stage, followed by tests which will completely cover the performance of the unit with respect to its electronic, mechanical, environmental, and human engineering requirements. The planning for the model program should have provided enough models of each unit, subassembly, subsystem, or system, to allow for shock, vibration, temperature, and humidity testing, as well as life testing of critical units. Past experience has generally shown that most types of equipment should be thoroughly life tested as early as possible in the model program. Short life of components discovered too late can produce an insurmountable logistics problem for the customer during early deployment and can result in a serious tactical situation.

Development Manpower

So far, the stages of development have been discussed with little reference to the organization of manpower required for such development. Some comment is in order on the organizational structure of the project and the kinds of people that are needed. It goes almost without saying that the kinds and number of people needed will vary throughout the project.

The success of a project depends very heavily on the choice of and the responsibilities invested in the project engineer. The size of the project should have an important bearing on the level of management vested with this responsibility. Placing the responsibility too low in an organization can be a limitation on the project engineer with respect to the delegations of authority he needs to conduct the job effectively. Placing the responsibility too high in an organization relegates the project to a position of sharing with many other duties the attention of the project manager.

It is not necessary here to dwell on the particular capabilities of the project manager. He must deal with many people including customer representatives, engineers, and subcontractors and obviously must have a background of training and experience to enable him to understand their language and their problems.

In a project of any substantial size, the project engineer needs a system design group to assist him in coordinating the efforts of all other groups and subcontractors. This group will ordinarily constitute about 5 to 10 per cent of the total personnel on the project and will vary in size and in composition with elapsed time. For example, in the study phase this group needs people of high analytical ability and keen insight into the customer's problem, mixed with a smaller number of experienced development engineers. Some members of the team may necessarily have their heads in the clouds since they may be working on the forefront of knowledge, while others in the group must keep their feet firmly on the ground if a practical recommendation is to ensue.

As the project progresses to the proposal evaluation stage, the bright ideas must be subjected to a searing examination by dedicated critics whose purpose is to determine objectively if the bright ideas are really bright when examined from all pertinent angles. The systems group must thus include one or more pessimists who must be well informed in the applicable scientific fields and perhaps be even better informed about the practical problems involved in reducing ideas to practice. The critic may be an old timer who has learned by long experience how to take a constructive negative attitude toward a proposed idea, or he may be a youngster with a special talent for asking embarrassing questions. Mutual respect can be maintained between proposer and critic by having them change roles on different jobs or even on different aspects of the same job.

The characteristics of the systems group will continually change and eventually, at the field test phase of the pro-

gram, it will be made up of people having particular capabilities in field testing operations and who are experienced in dealing with the customer at military proving grounds, firing ranges, or military test sites. The specific assignments and responsibilities of the group as the development job progresses may be listed as follows:

1) System performance requirements
2) Maintenance capability
3) Economic balance
4) Continual evaluation and analysis of system performance
5) System test specifications
6) Conduct of field test and analysis of results.

This emphasis has been put on the systems design group because of its importance in the processes of planing and in directly assisting the project engineer. However, as previously indicated, it ordinarily constitutes only a small portion of the people required for the enterprise as a whole.

As the project gets into the detailed equipment design phase, the effort rapidly mushrooms to include many people new to the project. Assuming that planning has been good up to this point, there is still a very great need for good management from here on out if the development is to proceed with efficiency and on schedule. Only a few of the points involved will be discussed here.

First, responsibility for every unit and subunit in the whole system must be assigned to a specific individual. He must understand that he is undertaking to meet the technical requirements and to meet them on the assigned schedule. It is clearly his duty to sound the alarm to the project leader as soon as he suspects that a precarious situation is arising.

Second, the best qualified available talent should be assigned to the various portions of the job. This frequently means getting outside help by subcontract and resisting the urge to do everything within the organization.

Third, the easy parts of the job must be held in step with the hard parts. To let the easy parts proceed at maximum rate may look like fast progress on the job as a whole, but usually results in inefficiency when the problems on the hard tasks demand changes.

Good fiscal management and planning is just as essential to the success of a development as good technical planning, but cannot be discussed further in this brief paper.

Conclusion

This paper has discussed some of the many facets of good project management, an important contribution in the development of useful and reliable equipment. Systems engineering, which many have found so difficult to define, may really have no better definition than simply all the things one has to do to insure a sound plan for carrying out a large development effort.

Systems Engineering*

R. H. JEWETT† AND R. A. MONTGOMERY†

Summary—**A description is given of practical systems engineering methods as applied to large military systems in an industrial environment. Particular emphasis is placed on a design approach which stresses minimum interconnections between subsystems and on system testing methods. Also discussed are system evaluation, management, and costs.**

Introduction

A "SYSTEM," for the purposes of this article, may be defined as an assembly of equipments or components chosen, arranged, and operating together so as to accomplish a certain defined task. This task is the "mission" by the military definition, or simply the "job" in a business sense. A system may contain other systems, which are then called subsystems. For example, a telephone network is a system insofar as it meets communication requirements; however, it is a subsystem when considered as part of an air defense system.

The nation's railroads are good examples of early large-scale systems. Such systems included rights of ways, tracks, rolling stock, fuel, stations, trainmen and other personnel, personnel housing, tunnels, bridges, and many other constituents. Railroad promoters who were poor system designers, either in choice of market or ability to meet competition, failed. This element of competition provides the only real criterion of successful system design and will be discussed in this paper.

In industry, teams of engineers are required for each of the principal systems engineering functions, *viz;* design, management, evaluation, and testing. Members of each of these teams must all approach their jobs with a healthy respect for, and understanding of, the other facets of systems engineering.

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Systems engineering, in particular, is evolving as a distinct branch of engineering practice. The systems engineer bases a new system design on known fundamental physical capabilities—future inventions cannot be scheduled for inclusion. The systems engineer must also leave the detail design of subsystems to others. Constrained from specializing, he must be skillful in interpreting the potentials and limitations of alternate system configurations.

The experience of the authors has been primarily with large-scale military systems for air defense purposes. Their work has been carried out in an industrial environment under continuous competitive pressure. It is hoped that this paper will convey some of the lessons learned.

Problem Formulation

Successful systems result from applications of technology at a specific time to a "mission" of current and continuing importance. An organization, in order to compete, must have internal or external access to the technological possibilities in each of many scientific and engineering fields and must also provide the special skills in synthesis required to select critical elements. The synthesis work is generally done under competitive pressure: either direct competition for a contract, or indirect competition for the same available funds.

A system is engineered with in certain limitations. Fig. 1 diagrams the constant pressure upon these boundaries.

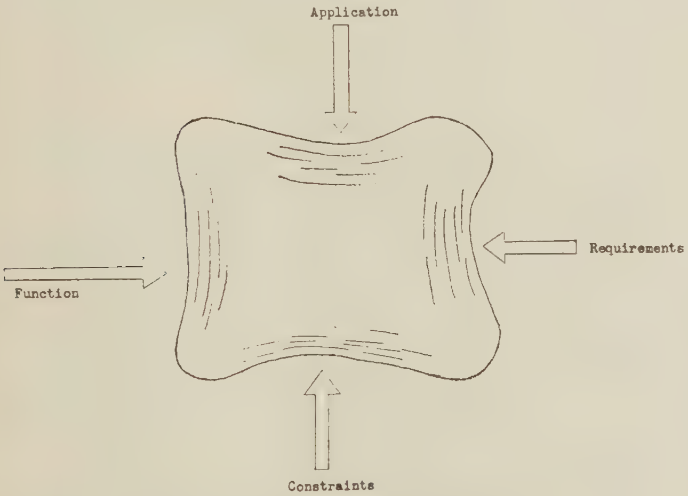

Fig. 1—Forces affecting system design.

Principal pressures are:

1) Function—what the system has to be designed to accomplish.
2) Application—the environment in which the system must function.
3) Requirements—the special features which the system must contain to satisfy the customer. These may include compatibility with other systems, use of other systems as subsystems, use of standard parts, and maintainability by unskilled technicians.
4) Constraints—the limitations imposed by specific circumstances under which the system design job is to be executed. Typically these are economy, time, manpower, size, weight, etc.

System Synthesis

Assuming a thorough understanding of the system requirements has been reached, system synthesis begins. Initially the search is for even *one* technically palatable solution to the problem. Frequently this is a long and sometimes unsuccessful venture. After a single technically satisfactory approach has been determined, variants and alternatives usually immediately suggest themselves.

From this point a parallel program evolves. On the one hand a simple mathematical model of the system is constructed, and preliminary system evaluation begins. At this time the evaluation consists of parameter studies directed towards obtaining a relative picture of the effects on system performance of varying critical parameters. The evaluation will use both the tools of simulation and game theory. However, in some cases the game theory analysis is replaced by competitive gaming. This gaming in some respects is the equivalent of the child's game of "Battleship, Cruiser or Destroyer." The essentials are to determine the outcome of a contest between two teams. One team is provided with the assumed characteristics of the system being tested. The other team is also granted a finite set of assumed capabilities. The ensuing game is arbitrated by an umpire whose evaluation provides the desired data.

In the other, or parallel, approach, the system configuration is established by the initial design team. Many of the critical system design choices are made during this period. It is important that this work be done soundly and carried far enough so that the subsequent step of system design execution does not bring too many unpleasant surprises. If the initial design is soundly carried out, then the remainder of the task will flow more smoothly.

The composition of the initial design team is important. The team itself must be fairly small and coherent, and must be able to draw on the organization's technical resources for technical inputs and recommendations. The output of the team is a system design document and configuration for the over-all system, including requirements and performance estimates for all subsystems.

System Design

Having established the preliminary system design to the point where it has passed the test of technical feasibility, and where it has been reasonably optimized by the evaluation team with respect to such factors as effectiveness, cost, reliability, etc., we come next to the problem of subdividing this rather broadly defined package into smaller packages, called subsystems, sub-subsystems, and components, which can be worked upon by a large body of designers of the actual hardware. The package in each case

must be discretely defined, such that minimum coordination between design groups is required. In other words, each package must not have too many strings sticking out that have to be knotted jointly with other groups.

Each subsystem definition must spell out:

1) The performance required.
2) The functional relationships to other subsystems and to the over-all system.
3) The test requirements.

In approaching this problem we must first be sure that the over-all system performance requirements as established by the preliminary design group are thoroughly documented. This document is the base line from which all work stems, and it must be maintained in a current—therefore dynamic—state throughout the life of the design activity. Next, we must make our initial definition of the performance requirements of the major subsystems, their sub-subsystems and finally, component performances, as required to provide the over-all system performance. At this point it should be emphasized that these requirements must remain flexible during the course of design progress, in order that performance deficiencies which are bound to show up in design and test of some subsystems and components can be accommodated by the extra performance achieved in other areas.

In addition to the performance requirements of the subsystem and components, we require definitions of the functional relationships between the various subsystems, again on a flexible basis which can adapt to new knowledge as the design progresses. These relationships between subsystems are variously called interties or interfaces. In general, the more sophisticated the system, the more interties it requires. When we ask that a system respond to a given situation with great rapidity and, in addition, in a manner which varies with small differences in a large number of factors, we are increasing the subsystem interties required. To illustrate, consider a passenger elevator. If we assume that it operates only between the first and second floor and that it has light traffic, it can respond more slowly to a simple pushbutton switch and use a simple off-on electric motor. If it must operate between several floors with high traffic, we want it to operate much faster to provide adequate service. No longer can we use a simple off-on motor, so we must provide control circuits which assure smooth acceleration up to high speed and smooth deceleration. Also, the control system must sort out the floor from which the signal comes. Now we're getting a number of interties between various parts of the system. The size of any system design job is a function of the number of interties between the parts of the system which in turn are governed by performance requirements (as in the elevator example). It is also a function of the size (number of subsystems) of the system. If, for example, we take a battery of our high-speed elevators in an office building and ask the control system to dispatch the elevators automatically, taking into consideration the number of people ringing at different floors, the time of day as to whether people are coming to work or going home, how full each elevator is in picking up passengers during descent, etc., we have a much larger and more complex system.

Our experience shows that good systems engineering requires a strong effort to keep the number of interties to a minimum in the interest of compressing development time, maintaining system reliability and achieving flexibility together with minimum development cost. It is most important to analyze these intersystem relationships and systematically reduce them until it can be shown that further reduction will have an unacceptable system performance degradation. There is a definite limit to the total complexity of a system which can be developed on a reasonable time scale, regardless of the man-power applied. The total complexity is directly related to the number of interacting functions or interties between various parts of the system. A very large system employing large numbers of designers can be effectively managed only if the number of interactions between its parts are kept down.

At this point it is interesting to consider how man affects the problem of functional relationship between subsystems. Man is a flexible, if somewhat performance-limited, machine. He is especially useful in minimizing system complexity if his performance limits are not exceeded. Let's go back to our elevator illustration. An elevator starter with average intelligence and limited training does a highly satisfactory job of elevator dispatching when he mentally juggles the factors of time of day, present positions of elevators, load density of the various floors, etc. As a result, such an elevator system provides service almost as effective as an all-automatic one and is certainly much simpler.

Having defined performance and functional requirements for the subsystems, we should now mention test requirements for these same elements. We cannot do an intelligent or even a workable job of component or subsystem design without considering the tests required and the manner in which the parts of the system will be assembled and tested. The test requirements must recognize the need to insure performance of each portion of the system, its proper function, its reliable operation under operating environments, and the compatibility of the testing with that performed on other system elements and on the assembled system.

We have discussed the requirements for organizing a system design job in terms of packaging the parts of the system for the design groups to go to work on. This has required a definition of performance and functional and test requirements. There is, however, one more aspect of work organization which should be considered, which is the scheduling. In order to keep control, the scheduling must be given top billing. To do this, we start with the over-all schedule indicating final system test dates required and work back to establish the dates for subsystem and even component testing. It is obvious that all the dates may have to be juggled several times in order for a compatible set to emerge. This process forces close attention to be paid to the realistic availabilities of components. The re-

sulting schedule, when approved by top management, is called the "master" schedule and can be modified only by top management. Equivalent schedule control is required in production.

The importance of scheduling is generally well recognized, but there are two facets frequently overlooked. The first is to make sure that all items of the system are included. Those most frequently missed are the support and test equipment in final product form. Support and test equipment as required for the development program is usually provided for, but the design of the production version is frequently missed in the initial scheduling. Consequently, it becomes the bottleneck in production and in effective use of the system in the field. The second item often neglected is flexibility in the schedule. Things never go as planned, and the schedules must take into account alternate ways of proceeding without affecting the final dates when one or more delays are encountered in some of the component or subsystems development.

The designers, in proceeding, must tackle the toughest and least certain parts of the problem first. Analysis and test should be programmed to yield critical answers at the earliest possible dates. As the design proceeds and provides answers on the performance realized by the various components and subsystems, these answers (both better and poorer than expected need to be coordinated with other subsystem design groups to rebalance the performance of the entire system. This in turn will cause a readjustment of the performance and intertie relationships originally set forth for the various subsystems making up the entire system.

System Testing

System testing covers not only factory and field testing, but also development testing.

It makes sense for the system designers to be responsible for the design of factory and field test equipment and for the test requirements and procedures which go with the testing. In every case we hold our own designers responsible for test requirements, even in those cases where the subsystem may be the responsibility of another company. In such cases, the other company should design and furnish the equipment for factory and field tests for their subsystems. The present trend is to have more and more of the subsystems designed and furnished by other companies, either as government-furnished subsystems or by subcontract. In either case, the prime contractor's role is becoming one of the assembling and testing the system, while manufacturing very little of it. Largely as a consequence of this, our factory layout is governed by the requirement of orderly assembly and test sequences.

We use a method in our operation which has several levels of test, in which the component tests may be level 6 and the smallest assembly of components may be level 5, building up larger subsystems at lower test level numbers until the final system test may be level 0.

It is obvious that with this kind of assembly and test procedure there is a problem of performance tolerances which is analogous to the tolerance problem on mechanical parts. The total system tolerance on performance is broken down in a systematic manner to the successively lower test levels. The tolerance on the small assemblies must be narrow enough so that when they combine with the tolerance of other subassemblies at a higher level they do not finally exceed the acceptable deviation for the entire system.

Fig. 2 shows percentages of floor area devoted to assembling and testing in a typical case. In choosing the number of test levels during the assembly process, we attempt to minimize the total time and cost of testing. If no tests are performed until final assembly there are bound to be many faults which are difficult to isolate and the assembly line gets clogged. On the other hand, the subsystem tests are also time consuming and costly, so there is an optimum number of test levels.

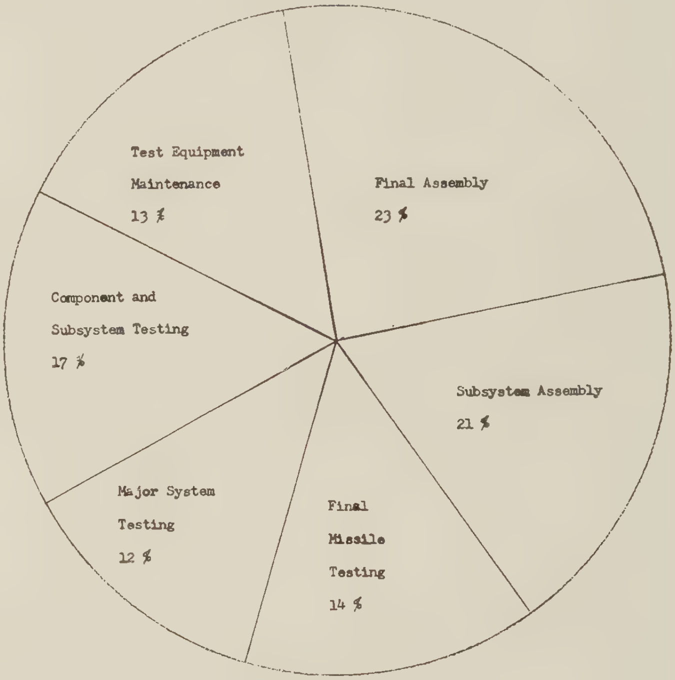

Fig. 2—Typical factory floor area requirements—for assembling and testing—excluding office space.

Regardless of what other test equipment may be used in the factory during the assembly process, the last checkout is performed on system test equipment which is identical to that furnished the customer for his use in the field. It is also wise to test in the factory to a tighter set of tolerances than is allowed for use in the field. This will provide some compensations for the degradation which occurs due to drifts with time, or less skill in field testing.

While there are many facets to development testing, such as component tests, breadboard tests, subsystem laboratory tests, etc., it is the flight test programs which are most interesting, meaningful, and visible, at least in missile development programs. We are able to identify three types of testing in missile flight test programs, namely, evaluation, demonstration, and exploration. This does not mean,

however, that each separate missile flight is flown exclusively for one of these purposes. In fact, many flights combine all three purposes. Evaluation tests, in the sense used here, are used to measure development progress in a gross sense since the successful ones verify the analytical prediction of system performance. They also serve to give confidence to the top technical management and the customer. The designers of the subsystems develop their confidence by the results of component and subsystem testing, but since the technical managers and customers are not so close to the subsystem test and analysis, they look to the flight tests for their evaluation of development progress.

In this connection, the authors have found that most designers are conservative and will advocate taking relatively small steps in the flight test program. It becomes necessary for those responsible for the work to force larger steps than the designers recommend. For example, the designer of a subsystem, such as an element of the guidance system or an auxiliary power plant, wants to fly it in the missile and telemeter back its behavior during several flights, before he is willing to hook it in as an operating part of the system. Our experience says that the right answer is to make all elements of the system operational parts just as soon as the hardware is available for flight. If the design and ground tests have been done well the parts will work in flight, and time and expense will be saved by reducing the number of figures required for the program.

Using this philosophy in one missile development program, only 18 missiles were required to prove the integrity of the basic airframe and propulsion. The guidance concept verification required 6 additional missiles. At the beginning of the program many people predicted it would require dozens or hundreds of missile flights to reach the same point.

Demonstration flight tests, under our definition, are those which show the customer that the system will meet the contract performance guarantees, that all elements of the system, including the support and test equipment, will function properly, and that the system is usable by the customers' personnel. These demonstrations normally culminate in tests performed by customer personnel preparing and operating the system using production prototypes of all items of system equipment.

Exploratory testing is that testing which is designed to find the performance limits to the system. It is of more immediate interest to the design engineer than to the customer, but it is most necessary for exploiting the growth potential inherent in the system. When subjected to limit testing, most of the system will prove to have more than design performance. By fixing up the weak spots, the system performance can be greatly improved at little cost in weight or complexity. As a rule, missile designers feel they have more difficulty than they should in getting exploratory flight tests scheduled. One of the reasons for this is that this limit testing often results in spectacular failures, such as structural breakups or explosions, when the limit is reached. Since missile flight tests are usually quite visible to the press and public, the customer doesn't relish testing which courts publicly visible failures, no matter how worthy they may be. In fact, the design organization, particularly if it is part of a company making consumer products, is also reluctant to have unfavorable publicity. Fortunately, we have been quite successful in combining test objectives wherein the exploratory or limit testing is done late in the flights, after the demonstration objective has been accomplished. Maximum range tests and maximum maneuver acceleration tests are typical of those which have been done.

System Evaluation

Other than live system testing, the two main facets of system evaluation are:

1) System performance determination
2) System application analysis.

Both of these contribute to the understanding of the system's inherent capabilities and its usefulness for any proposed application.

System performance determination is basically the measurement of the system's ability to accomplish the job for which it has been designed. The tools required include facilities (analog, digital, or both) and a trained analytical staff. The use of simulation techniques as a design and evaluation tool is well known. Extensive digital simulation of complex systems requires considerable effort and time. Consequently, analog simulation techniques are used as well as digital. In the early stages of system design it is still necessary to combine analytical or graphical predictions of subsystem performance with estimates of over-all system performance. This situation is required by the lead time necessary to prepare the appropriate digital or analog simulations. Extensive simulations allow us to study the behavior of a system as significant parameters are varied to an extent that would not be possible by actual system tests. It has been our experience that analog simulations are primarily valuable for giving insight and improved understanding of a problem, but that digital techniques are required for accurate analysis of complex systems. There is much progress yet to be made before simulation techniques contribute their full potential to system design.

System application analysis or operation analysis relates to the study of the behavior of the system in the environment in which its use is planned. Exterior factors affect the performance of the system in a specific application, and results are obtained which apply only to the particular application being considered. These studies may reveal deficiencies in the system which should be removed for effective over-all performance. These studies may be considered as "outwardly" motivated, rather than "inwardly" motivated as are the system performance studies. The commercial airlines make extensive use of operation analysis techniques. Paper airplanes are flown over specific commercial routes to establish the economics and other features under

changing weather, traffic load, schedule arrangement, and other variations. These studies help the airlines establish requirements for new airplanes. After a specific airplane has been ordered, the studies are intensified to provide an evaluation of the potential value of the airplane to the line and to determine the optimum manner of applying the airpane to the routes to be served.

These studies determine how many of a given type of aircraft should be ordered, how much ground support equipment will be required, and what fares and load factors are necessary for over-all profitable operation. Mock-ups of the aircraft are built by the customer airline in addition to the airframe manufacturers. These are used to experiment with seating arrangements, meal facilities, stewardess requirements, etc.

Management

System management implies a "cradle to grave" responsibility. In the systems engineering field this means a continuity of work from first concept stages through to final obsolescence of the last articles in field use. Ability to provide this systems engineering and management function is unique with commercial manufacturing organizations. Only these organizations have both the incentive and the mechanism to carry such programs through.

The organization to accomplish the development and test of large systems can take many forms. There are, however, certain basic requirements, which are perhaps fulfilled only by organizations which undertake large system design responsibilities. First, the organization must be fluid, to provide growth for individuals without loss of their experience to the program. This is essential because of the length of time required to complete each program and the relatively few major programs under work. Second, the organization must evolve as the program goes from the early concept and design stages through test and production.

Top management must be provided assurance that the work is progressing satisfactorily. To this end, the organization must provide for planning and coordinating functions, "doing" functions, and a "conscience" function. The "conscience" is used to keep the "doing" honest; the planning sets goals and monitors progress. Actual organization tables must fit the personnel available. The organization must accomplish the above functions to be satisfactory to management.

Fitting the system function into this over-all organization creates many problems, as systems work cuts directly across normal channels of hardware design and testing. What is basically needed is to have, at early stages of the program, a system design activity which provides cohesion for the program. Personnel assigned to this activity must have a thorough understanding of the design principles and objectives.

During later stages of the program, the concept is now firmly established and the work packages discussed above under Systems Design are well defined. At this point, the systems design responsibility is primarily to insure both compatibility between subsystems, and economical and timely design.

In using successfully the capabilities of other industrial organizations for developing large and critical subsystems, the key to success lies in the rigid application of a few simple rules. These are:

1) Specify only the critical performance requirements.
2) Minimize the functional interties with other subsystems and then specify this minimum as requirement.
3) Specify the philosophy to be used in such matters as reliability, design trade-offs, growth potential, flexibility, etc.
4) Let the other organization execute the design on its own.
5) Maintain careful monitoring of progress by noting the achievement or lack of same for preselected key development progress points.

If this monitoring shows the subsystem development to be in trouble, insist that the responsible company fix its difficulty. Do not try to do it for him by taking over. It often seems easier to get in and do the job yourself—but do not. It only leads to more trouble. Sometimes we have found that it is necessary to provide temporary help in the form of skilled engineers, managers, and shop people. This must be done on the basis of their working for the management of the company in trouble, with care taken to see that they report to the correct management level. Our theory is to help him to get out of his trouble, not to solve his problem for him. We know this is the way to get strong and willing partners.

System Costs

Costs, of course, are of paramount importance in the implementation of a military system. It is essential to have early in the design and implementation a realistic understanding of the extent of funding available to achieve a particular mission. For example, there is competition for funds for offensive and defensive missions. National military policy coupled with government economic policy determines the extent of funding available for offensive weapons. Again, within the offensive aircraft and missile mission there is competition for funds between long-range bombers, carrier-based reconnaissance aircraft and missiles, submarine-based missiles, ICBM's, and IRBM's.

Development costs of large-scale military systems become very large, and in fact can exceed production costs if only small quantity production runs are procured. This obviously is an undesirable situation, which hopefully can be avoided by realistic planning.

We often hear the argument that a particular weapon system development was worthwhile from the viewpoint of knowledge gained and capabilities established, even when implementation was not carried out. We submit that this is an expensive form of development. There is a need, however, for judicious funding of critical component

developments without requiring these developments to be justified in all cases by being a known part of a weapon system.

Production costs with complex military systems tend to go down a rapid learning curve. As a result, increased procurement quantities can be achieved with significant savings in dollars. In fact, in typical cases increases of 100 per cent in production orders may only result in a 33⅓ per cent cost increase if the quantities are procured over the same total time period. This bears very strongly on the problem of major system changes.

Although a new model of a military system may be technically available, building it is not always desirable if the same objectives can be achieved with the older model even at the expenses of more required equipments. In this case we balance up the costs vs the effectiveness per unit. These trades must be judged differently if extremely high-level performance systems are desired. For example, if the mission demands nearly 100 per cent success, different answers would be reached.

Commitments to Production

Complex systems are characterized by the long lead time required from the initial concept to the time at which a significant quantity of equipment is in operational use. The lead time is not directly proportional to the complexity, but it is a function of the complexity, the degree of state-of-the-art improvements required, and the manner in which the design and implementation job is attacked.

Procurement policies which are based on a proven prototype test preceding production ordering are reasonable and adequate for military purchase of systems of a low order of complexity. These policies, however, are completely inadequate for achieving operational readiness of complex military systems. It has been our experience that, if the basic technology is understood and if the feasibility of the concept can be established by analysis and test, then a severe penalty results from waiting until complete production prototypes are available before committing a system to production.

Systems consist of many equipments, some of which will be found initially to be poorly conceived or executed in design. In all cases, however, the over-all system can be made to work, with the recognition that problems are present in specific areas. The supposed saving of waiting until a complete design can be chosen and proven before commitment to production is more than balanced by the true cost of producing equipment several years later than is otherwise possible. In fact, all successful weapon systems which have had large-scale use in this country in the past fifteen years have been committed to production prior to availability of completely engineered prototypes with all the supporting data and handbooks.

This point is belabored here in the hope of destroying false illusions of economies and savings. The greatest economy is not to do the job at all. If the job needs doing, then production commitments can be made with confidence early in the development program. Care must be taken, however, to prevent these commitments from causing premature design freezing or unnecessary rigidity in the development program. This leads naturally to the subject of the next section.

Changes

Control of changes is a very difficult problem during a system development and production program. On the one hand, everyone recognizes that changes are necessary; on the other hand, no one wants to go to the trouble of making them. The costs of changes are greatly amplified by the amount of coordination necessary to insure that the system will be compatible after the change has been effected. Normal procedure is to establish change boards which have representatives from each department of the organization. These change boards are responsible for putting together a complete description of a change, the effect of the change on other parts of the system, the cost and timing associated with the change, and the benefits to be accrued, based on all these factors. A decision can then be reached, and the change ordered or not. The key to successful control here lies in the clear definition and establishment of subsystems in such a way as to make them as mutually independent as possible. Whatever the change procedure adopted, firm control is necessary to avoid chaos.

Acknowledgment

The systems engineering methods described above have evolved from the experience of the entire engineering department of the Pilotless Aircraft Division of the Boeing Airplane Company. All members of this department have directly or indirectly contributed to this paper.

Weapons Systems Management*

T. L. PHILLIPS† AND I. A. GETTING‡

Introduction

IT IS a platitude that any successful weapons system requires inspired engineering leadership characterized by sound judgment and a broad understanding of military needs. In the following comments the formal aspects of weapons systems engineering are presented. While these formalized steps are essential to a successful system, at each step there is also the need for compromise or innovation. Lack of judgment where a sensible compromise is required can result in a monstrous system. Lack of innovation and inspiration can result in a stale system.

The very word "system" implies a coordinated and consistent engineering task. Leaving out for the moment such aspects of prudent engineering as reliability, standardization, and due respect for peripheral details that include spare parts, instruction books, test equipment, etc., there still remains the need to integrate the main task at hand. In general, a weapons system has to perform some task. In modern weapons systems, this task is generally a complex one involving many interrelated technical features. It is, in general, the realization of this one fact which has led to systems engineering in which the over-all technical management responsibility is placed in one person or agency. This is in contrast with earlier systems of management in which various military items were designed and purchased independently, and the system was then put together by operational people to form a military entity. Such a system prevailed when field generals deployed infantry, cavalry, and field artillery. There was very little engineering relationship between the saddles, the pistols, and the mortars. On the other hand, today military weapons such as missile systems combine aerodynamics, electronics, propulsion, explosives, and ground support equipment into an internally consistent dynamic and kinematic system. Harold Hazen of the Fire Control Section of NDRC during the war quite properly stated that present weapons systems are generally defined by high order differential equations. The old concept of separate engineering and procurement is comparable to taking such a differential equation and contracting out each separate term, term by term. It is not surprising, therefore, that the solution consisting of such independent attempts at solution was equally monstrous.

Placing Responsibility and Defining the Problem

A new weapon system is born with the requirement for an advanced tactical, strategic, or defensive capability. The requirement is operationally defined by a set of military characteristics usually prepared by the using agency of one of the three services. The characteristics define such broad parameters as the primary and secondary missions, the operational environment, the desired range, effectiveness, reliability, and degree of mobility of the system.

The major burden of system engineering falls on the technical agency and the prime contractor in varying amounts depending on the particular service and the type of weapon system. It is important that the role and responsibility of each be well defined early in the development. Proper system engineering is feasible either for the case wherein the technical service is strong enough to retain technical control of the system, relying on industry only for manufacture, or for the case wherein systems control is assigned to a strong prime contractor when development is initiated, and broad latitude is allowed toward the solution of the problem. In either case the responsibility is clearly defined, which is of the utmost importance. The great danger comes when a technical agency or government laboratory is not strong enough to manage a complete program, but still desires to dabble in it. In this case, responsibility cannot be clear and an inferior product delivered on a delayed time scale is the inevitable result. A great many weapon developments drift into management along this compromised middle road. It is a compromise of expedience and a leading deterrent of proper system engineering.

Assuming the responsibility is defined, the next step is to define the problem. The operational characteristics of a weapon system must be translated into precise technical requirements. We must ask ourselves early, "What are the precise technical problems we are trying to solve?" In doing this many times the answers are readily forthcoming and we avoid vague solutions of imaginary problems which often result from inadequate definition.

A weapon system implementation is divided into four time phases as follows:

1) Feasibility study
2) Critical component development
3) Prototype development
4) Production.

Sometimes it is difficult to recognize the distinct division of these phases, especially in an accelerated program. However, for purposes of this paper, we will assume the division to exist.

Feasibility Study

During the feasibility study, a system engineering nucleus of key people must be assigned to the problem. These people should have the broadest possible systems experience, although men with specialized technical pro-

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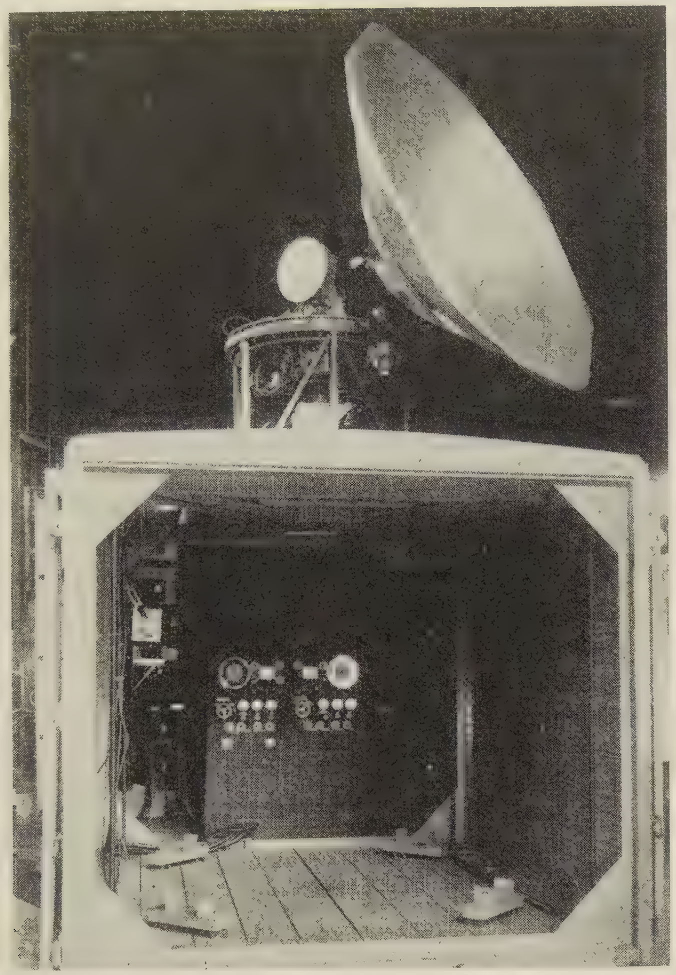


Fig. 1—Readers may be interested in this photograph of the Laboratory, breadboard XT-1, which became the SCR-584 in production.

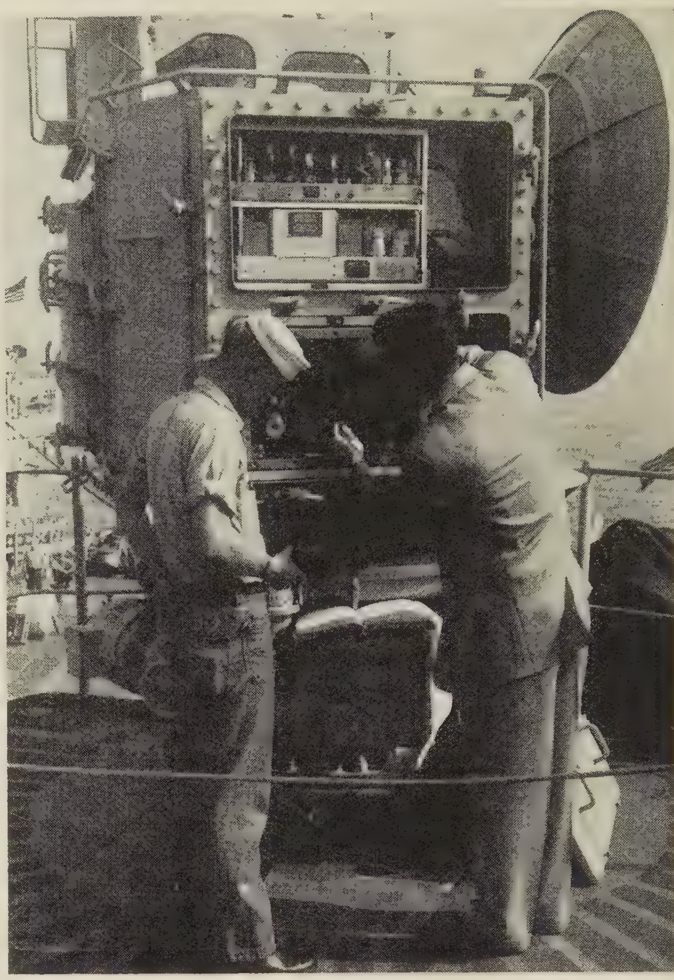


Fig. 2—Of historical interest is this photograph of the first fully integrated automatic radar tracking fire control system in the Navy—GFCS MK. 56.

ficiency in such major fields as radar, infrared, communications, controls, aerodynamics, propulsion, and armament must be included. Clearly, the feasibility study is a time for concepts and ideas, with conceptual thinking being stimulated by a free exchange of ideas. Often many ideas will not be feasible, and the best critics in pointing this out will be nonoriginating members of the same group.

After the number of approaches is narrowed down, often two or three will still appear to be feasible. Here the methods of operations research and analysis must be called on to evaluate competitive solutions and choose an optimum one. To accomplish this, simplified mathematical models are used and comparisons are made based on several criteria, such as reliability, cost, weight, mobility, etc. However, operations research is no better than the assumptions which are made, and to the extent that these assumptions may become more and more involved, the results of these studies must be carefully evaluated as to their realism. Often a decision may be required which, while guided by the results of the study, will nevertheless be based primarily on the experience and judgment of the systems engineer.

It is the object of the feasibility study to choose an optimum way of accomplishing every objective of the system. From this point on, every major parameter of the system is defined. It may subsequently prove that unwise selections were made, and alternate solutions must be explored. These explorations must then be made in parallel and on the side, while the major system development proceeds along its designated path. Should an exploration prove to find a solution more desirable than the one designated in the defined system development, this is then substituted for the inferior solution. The important thing is that after the feasibility study there be but one established approach to any particular problem at a given time, and that this be defined in all of the pertinent design data manuals. Only in this way can a complex weapon system be designed with compatible components by design agencies often laboring in well-separated geographic locations.

A second objective of the feasibility study is to evaluate the effectiveness of the weapon system as defined at the end of the study. Measures of effectiveness in graphical form must be available, depicting such parameters as zones of effectiveness, kill probability, rate of fire, system costs, manpower requirements, mobility, transportability, and the maintenance and support plan.

During and at the end of the feasibility study, careful reviews should be made of the system with the using agency. These reviews are usually in the form of presentations or conferences and are of the utmost importance in the development cycle of the system. Without these reviews it is not possible for the contractor to anticipate and interpret all of the operational requirements the user has in mind, nor is it possible for the user to anticipate the contractor's method of approach and its effect on his requirements.

After the feasibility study, arrangements must be made for periodic reviews wherein contractor and user have a chance to exchange ideas. Without this cross fertilization of ideas, science and industry might well develop technically superior weapons that are operationally of very little practical value to the user.

Critical Component Development

The next phase of the development cycle is that of critical component development. There are two reasons why this phase is separate and distinct from prototype development.

The first is that the weapon system requirement has become so critical that there has not been time for basic research to supply all the tools necessary for the system's realization. Therefore, in certain critical areas the weapon system is pushing the state of the art, and critical component development or accelerated research must be accomplished to ascertain its feasibility.

The second and very practical reason is that development programs are not always adequately funded. In this case, choices must be made on those components whose development on an early time scale is most necessary, either because of lead time or their critical nature. For example, a missile airframe must be developed before a means of handling it, and a guidance system, before a means of maintaining it.

During the critical component development phase or earlier, some of the major subcontractors of the system will be engaged. Indoctrination of the subcontractor in the system philosophy is a very important task. One particularly effective way of accomplishing this is to invite the subcontractor's key people to spend a period of two to three months at the prime contractor's facility, and accomplish there most or all of the preliminary design. During this phase the compatibility of the design is assured, and the mode of operation and liaison ties are established.

For effective subsequent liaison the prime contractor must be staffed with men expert in the technical proficiency of the subcontractor. They have the important role of continually reviewing the subcontractor's design and continually interpreting system requirements in a technical language which the subcontractor can readily understand.

The question is often raised as to how much the prime contractor should subcontract out and how much he should retain for in-house development. That there will be subcontractors in the development of a major weapon system almost goes without saying, because the complexity of today's weapon systems is such as to make it extremely unlikely that a single contractor possesses all of the necessary skills within his organization.

On the other end of the spectrum, it has become popular to consider prime contractors who subcontract all development and perform only a management and coordination function. There is a danger in this approach, however, since the prime contractor cannot really have the competence to manage unless he gets his hands dirty in hardware and has tackled some of the difficult development problems first hand.

Then too, the research and development phase of a program is not financially rewarding to a profit-motivated industrial concern. Therefore, it becomes important for the prime contractor to retain a certain percentage of the weapon system development in the house to reap some of the financial rewards of subsequent production. This also affords the allocation of the highest calibre developmental people and retains the enduring support of management.

Considering both these factors, it is our estimate that a prime contractor should retain for in-house development somewhere between 30 and 60 per cent of the system, depending on the particular situation.

Prototype Development

The prototype development is a phase which must culminate in a complete system demonstration and lead directly to production releases. It is also the phase where reliability will or will not be designed into the system.

Of course, reliability begins with the basic concept of the system. If the basic concept is marginal, or if it simultaneously requires an unreasonably high degree of performance on a number of its elements, such a system will be operationally unreliable. The stress of war and the general deterioration of equipment in field use demand margins of safety in concept.

In addition, the designer must design adequate margins of safety into each of the component parts. However, as a double check a Quality Assurance Department must be available to evaluate all aspects of a given design. These include not only what is normally considered reliability, such as the ability of components to withstand environment with safety margins, but a complete evaluation of the degree of sophistication of the design and the ease of its testing, handling, and maintenance.

Where missile systems are concerned, design evaluation is extended one more stage to the flight test facility. Here, especially where complete systems are assembled and firing operations are conducted, it is important that the contractor have high calibre personnel capable of evaluating design deficiencies and reporting them back to the home plant for corrective action.

With three layers of design evaluation and rapid reaction it is possible to eliminate at an early date those

design flaws which would otherwise have crept into the system.

The center of project control and decision is the project engineering team which was established during the early phases of the feasibility study. This team must bring the design specialists together to evolve a compatible design, must enforce corrections of design deficiencies, must maintain liaison with the flight test facility, the production facility, and the government agency, and must establish and maintain system schedules.

The key man in the project team is the senior project director. In a complex weapon system, rule by committee is not possible. Somehow, in any system one man must accept responsibility for decision and for the ultimate outcome of the development. The natural attributes of this man must qualify him to lead, to stimulate, to inspire a team spirit, and to promote.

A seldom recognized attribute, however, is also the ability to say "NO!" In every large research and development organization, there is a plentiful supply of ideas and inventions. Some of these ideas buy a great deal in capability and contribute greatly to the effectiveness of the weapon system. Others, while adding some effectiveness to the system, do so at a high cost in complexity and a significant reduction in reliability. Still others, while adding effectiveness, do so in a time scale to affect production schedules or seriously alter the logistic and support plan. It is the duty of the senior project director to evaluate these "improvements" carefully and unemotionally and to keep the program from being sidetracked by changes that would delay its timely availability or would otherwise have a detrimental effect on its operability.

We would hate to see the system where every "improvement" that was ever conceived became incorporated into hardware.

Production

The production phase of a weapon system is a difficult one because it is very seldom initiated with completely frozen design information. To delay production until this information is complete causes a serious lag in our operational capability and tends toward the production of an obsolete weapon. The basic question is, therefore, when should production be initiated in a weapon system development?

Experience has shown that a feasible time to initiate at least pilot production is immediately after a successful research and development demonstration indicating that at least the primary objectives of the military characteristics have been met.

There are many long lead time items associated with the initiation of production. Among these are facilities planning, the transfer of information in properly documented form, the processing of tooling and test equipment, the establishment of vendors, and the training of production personnel.

Concurrently, service activities must be conducted along the lines of training of key personnel and service evaluation tests of the equipment. During this preproduction transition period, large numbers of production and service people become acquainted with the weapon system, but relatively small numbers of equipment are actually produced.

In the meantime the design information is not finalized, because of two general types of reasons. First, design deficiencies have been uncovered as a result of the first full-scale system demonstration, environmental tests, or the very act of phasing into production, and corrections for these deficiencies are considered mandatory. Secondly, even during the time period of the development the threat has changed, requiring an incremental effectiveness increase in the military characteristics; this change in the weapon system is also considered mandatory. To meet these requirements, a product improvement program is conducted concurrently with pilot production. This is rather a hectic period because releases to production of improvements must be made prior to initiation of the large production buildup. If this is done, compatibility of delivered equipment can be maintained through the media of retrofit kits and an alert field service organization.

As time goes on, it becomes progressively more difficult and costly to retain system compatibility with major production changes. Hence, it becomes economical to have a cutoff date on all but routine changes.

Unfortunately, the rapid advances in technology cause an ever increasing threat to the security of our nation. Thus, it may be that the system in production will not adequately meet the foreseen requirements. At this point, it is both judicious and economical to concede that the developed system will have a limited span of useful effectiveness, and to meet the increased threat a second generation system must be initiated.

And thus the cycle begins all over again.

Contributors

L. I. Davis

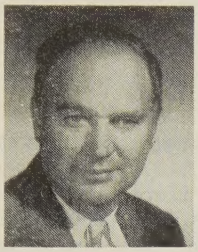
Leighton I. Davis was born in Sparta, Wis., on February 20, 1910. He entered the United State Military Academy in 1931, began his flying training following graduation in 1935, and received his wings in 1936. He holds the rating of command pilot. He has received the M.S. degree from M.I.T.

His first tactical assignment with the Air Force was as an engineering officer, Sixth Pursuit Squadron, 18th Group in Hawaii. In January, 1939, he became an instructor in the department of mechanics at West Point, and in 1942 helped establish the Basic-advanced Flying School for United States Military Academy cadets at Stewart Field, N.Y. The following year he was transferred to the Engineering Division at Wright Field, Ohio. During the next five years there he was technical executive to the chief of the Armament Laboratory, and then chief. In March, 1948, he became chief of the Applied Research Section of the Air Materiel Command, which became the Office of Air Research in February, 1949. After graduation from the Air War College, he was named Deputy Commandant of the Air Force Institute of Technology, and, in 1951, Commandant.

After the formation of the Air Research and Development Command, General Davis was transferred to Baltimore as Director of Armament. He then served as Director of Development until September, 1954, when he was named Commander of ARDC's Air Force Missile Development Center. He became the Deputy Commander for Research and Development at ARDC headquarters in August, 1958. In September, when the organization increased its efforts in basic research, his title was changed to Deputy Commander for Research.

While instructor at the USMA, the general received the Legion of Merit for his development in 1939 and 1940 of electronic pressure-time and pressure-volume equipment used in instruction at the Military Academy. He received the Oak Leaf Cluster to the Legion of Merit in 1946 for his work in designing and developing the A-1 series of gun-bomb-rocket sights for fighter aircraft. The Institute of Aeronautical Sciences chose him to receive the Thurman H. Bane Award for 1946 for his work in developing fire control equipment.

He was recently awarded a patent for an electronic air warfare game that illustrates modern warfare techniques and nuclear weapons' influence on target selection.



I. A. Getting

Ivan A. Getting was born on January 18, 1912, in New York, N.Y. He has received the B.S. degree from Massachusetts Institute of Technology, and the D.Phil. degree from Oxford University in England.

As Director of Division 8 of the M.I.T. Radiation Laboratory, he was responsible for all fire control developments of that laboratory. These included the SCR-584—the first automatic microwave tracking radar. It was one of the most successful radar systems of World War II, and saw service not only in its primary use as anti-aircraft fire control, but also in tracking V1's and V2's and in controlling tactical airplanes and missiles. He was also responsible for the development of the gun fire control system Mark 56 for the Navy. This was the first Navy automatic integrated fire control system, and is still in operational use in the Navy.

For these contributions, among others, Dr. Getting was awarded the President's Medal for Merit and the Naval Ordnance Development Award.

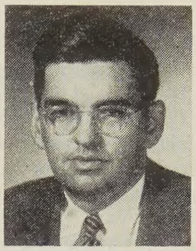
Since the war he has been professor of electrical engineering at M.I.T., assistant for development planning in the U.S. Air Staff, and, for the last seven years, Vice-President of engineering and research at the Raytheon Manufacturing Company. He continues to serve as a member of various government agencies.

R. H. Jewett

Robert H. Jewett was born on April 21, 1910 in Rice Lake, Wis. He received the B.S. degree in aeronautical engineering at the University of Minnesota in Minneapolis.

In August, 1937, he joined the Boeing Airplane Company in Seattle, Wash. Since 1945 he has been associated with Boeing's guided missile developments. He is presently chief engineer and assistant general manager of the Pilotless Aircraft Division.

Mr. Jewett is an Associate Fellow in the Institute of Aeronautical Science and a Fellow in the American Rocket Society.



R. A. Montgomery

Richard A. Montgomery (S'46—A'49—M'55) was born on January 11, 1919, in Canada. He received the B.A. degree in physics from the University of British Columbia in Vancouver in 1940, and the Ph.D. degree in electrical engineering from the California Institute of Technology in Pasadena in 1948.

In 1951 he joined the Boeing Airplane Company, Seattle, Wash., where he is presently staff engineer of the Pilotless Aircraft Division, Weapon Systems Staff. In this capacity he is responsible for advanced missile systems analysis, and investigation and evaluation of new methods of weapon guidance.

Dr. Montgomery is a member of AIEE and Sigma Xi.

H. G. Och

Henry G. Och (SM '57) was born in New York, N.Y., on March 16, 1907. Shortly after receiving the B.S. degree in electrical engineering from New York University in 1927, he joined Bell Laboratories, where he is now Director of Missile Systems Development.

His first work was the design of filters and networks for carrier and transatlantic radio systems. In 1936 he transferred to the mathematical research department, where he was a consultant on transmission networks and feedback amplifier circuits for carrier telephone systems. In 1940 he turned to military work as consultant and designer of electronic anti-aircraft directors. He continued this work during World War II, taking part in basic system analysis and planning for anti-aircraft directors and many types of radar and fire control computers. He later supervised computer design of postwar anti-aircraft fire control and radar systems. In 1952 he was named to head a subdepartment in airborne equipment design and was given responsibility for development of bombing and navigation systems. With his appointment as Director of Missile Systems Development in 1957, he assumed responsibility for the Nike Hercules project at Bell Laboratories.

As a member of the National Academy of Sciences, in 1957 he took part in a study for the Air Research and Development Command. He has received a War Department and Navy Department award for outstanding contributions to the Office of Scientific Research and Development during World War II.

Mr. Och, who has been awarded more than 20 patents, is a member of Iota Alpha, Tau Beta Pi, and Eta Kappa Nu.

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Thomas L. Phillips (M'51) was born on May 2, 1924 in Turkey. He received the B.S. and M.S. degrees from Virginia Polytechnic Institute in Blacksburg, and did further graduate work at New York University toward a doctorate degree.


T. L. Phillips

He has been with the Raytheon Manufacturing Company for the past eleven years, continuously engaged in missile development. As manager of the Systems Department of Raytheon's Missile and Radar Division, he contributed significantly to the development of the Navy's all-weather air-to-air missile, the Sparrow III. For this work, he was awarded the Navy's Meritorious Public Service Citation.

After this, he became program director for the Army's surface-to-air low altitude missile, the Hawk. The Hawk is an integrated weapons system consisting of all the necessary functions from detection to destruction of the target.

For the past two years, Mr. Phillips has been manager of Raytheon's Bedford Laboratory. He has served as a member of several government committees, including the National Advisory Committee for Aeronautics, the Research and Development Board, and the Weapons Systems Evaluation Group.

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William C. Tinus (A'31—M'36—SM'43—F'51) was born in Chicago, Ill., on October 18, 1905. He graduated from Texas A. & M. College with the B.S. degree in electrical engineering in 1928. He immediately joined Bell Laboratories, where, during the early years of his telephone career, he specialized in the field of mobile radio systems for civil aviation, police, and military applications. He made major contributions to the development of radiotelephony for use in these fields.


W. C. Tinus

During World War II he was responsible for the development of various radar equipments, computers, and fire control systems for the armed forces, and served as part-time consultant to the War Department. After the war he directed several long-term military development projects undertaken by Bell Laboratories, including the Nike Guided Missile System for the Army. In 1949 he was named acting director of Military Electronics Development. Two years later he was appointed director of Military Electronics, and in September, 1953, he became a Vice-President of Bell Laboratories, in charge of military development.

He has served on many technical advisory groups for the government. At various times he was a member of the Radar Panel, the Technical Evaluation Group, and the Committee on Guided Missiles for the Research and Development Board. At present he is a member of the Steering Committee of the Advisory Panel on Electronics for the Assistant Secretary of Defense for Research and Engineering. He is also a member of the Army Scientific Advisory Panel and the Air Force Science Advisory Board.

In 1954, he was awarded the honorary degree of Doctor of Engineering by his alma mater. He was cited for his work in radiotelephony and in the development of ultra-high-frequency mobile equipment, and for his service to the government and in the administration of Bell Telephone Laboratories.

Dr. Tinus served on the IRE board of editors for six years. He is also a member of Tau Beta Pi, Eta Kappa Nu, and the American Ordnance Association.

INFORMATION FOR AUTHORS

The PGMIL TRANSACTIONS is intended to bridge the gap between the various disciplines contributing to military electronics. Since this includes most of the branches of electronics, the military, and many fields which are associated with but not actually within the realm of electronics, it is essential that the papers published be of broad interest. The emphasis should be on readable, thought-provoking material that stimulates an attitude of open mindedness and curiosity.

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Mathematical concepts—Applications and implications of modern mathematical methods.

Associated subjects—Survey of fields that are neither military nor electronic but which are important to the advancement of military electronics.

Manufacturing—Industrial and military problems of reliability, quality control, etc.

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